Airborne and spaceborne ice sounding of Antarctica, Mars and Europa

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Summary Satellite-based radio echo sounding technique is of interest to the Earth science community over Antarctica and Greenland, as well as to the planetary science community for exploring subsurface structures of Mars and Europa. Pioneered by the Mars exploration community using MARSIS radar on board the Mars Express mission, such a technique has demonstrated ice sounding capability down to a few kilometers. This paper presents an overview of ESA's activities in the areas of Earth Observation and Planetary Exploration for preparing future satellite-based sounding missions. These activities include: (a) establishing observational requirements in consultation with the user communities; (b) understanding VHF/UHF wave penetration, propagation and scattering within the subsurface medium; (c) designing radar payloads and satellite systems which respond to the observation requirements; (d) developing data processing algorithms for enhancing resolution and sensitivity. The BIOMASS P-band Synthetic Aperture Radar (SAR) mission, a candidate among the ESA's future Earth Explorer missions, represents a unique opportunity for exploring ice-sheet of Antarctica and Greenland from space.

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Introduction

The satellite-based remote sensing community has been using gravimetry and magnetometry techniques to infer the internal structure of planets including that of the Earth. However, these indirect techniques have inherent limitations such as low spatial resolution, low sensitivity and non-unique inverted solutions, the latter requiring prior assumptions on the internal structure under investigation. The technique of satellite-based radio echo sounding was demonstrated for the first time by the MARSIS low-frequency radar on-board the Mars Express satellite (Nielsen, 2004), proving the existence of dust-covered pack-ice as well as surface water ice at the North Pole.

Terrestrial ice-sheets

On Earth, there is an increasing interest in enabling satellite-based radio echo imaging of the global, three-dimensional structure of the Antarctic ice-sheet (Rommen et al., 2004). A satellite-borne sounder would naturally provide global coverage, including that of Greenland, with homogeneous measurement characteristics. Its independence of remote measurement locations and the harsh in-situ environment makes it an attractive alternative to airborne surveys, which are often faced with considerable organisational and logistic hurdles. With a recent ITU allocation in 2003 at P-band (435MHz) for space-based active sensing of Earth, the prospect of such a radar mission has become realistic. The focus of the Earth sciences community, concerned with climate change and its consequences on Earth's two largest ice reservoirs, namely Antarctica and Greenland, is aimed at developing a better understanding of the possible evolution of the ice-sheets and their potential feedback on the coupled Earth system in the long term (hundreds to thousands of years). Most recently, attention has been concentrated on the stability of the West Antarctic Ice Sheet, a marine ice sheet with its bed below sea level and margins which are floating (see next section).

Mars

The existence of thick layers of subsurface and surface water ice on Mars, confirmed by the Mars Express mission, gives rise to speculation that subsurface ice may extend down to deeper regions where it is warmer, raising the possibility that caverns of melt-water exist. The next planned mission, SHARAD on-board the Mars Reconnaissance Orbiter, represents the next step onwards from the MARSIS radar. Its primary objective is to sound with high depth resolution in selected areas, dielectric interfaces to depths of up to 1km in the Martian subsurface and to interpret these interfaces in terms of the occurrence and distribution of selected materials, including rock, regololith, water and ice. Future sounding missions to Mars will provide observations with even higher spatial resolution and better coverage. The existence of an ionosphere, although less dense than that of the Earth, would make such observations difficult due to signal dispersion and scintillation.

Europa

Voyagers I and II, followed by the more recent Galileo mission, gave rise to the hypothesis that Europa, one of the four moons of Jupiter, has a small metallic core surrounded by a rock-shell. This rock layer may be in turn surrounded by a deep salty ocean of some 50km depth which is insulated on the outer surface by an ice-crust of several kilometres thick. The series of lines and ridges that criss-cross the ice surface are structurally similar to terrestrial polar pack ice during spring thaws. Geological evidence points towards the existence of tidal flexing effects caused by Europa's eccentric orbit around Jupiter. The goals of a mission to Europa include answers to fundamental questions, notably: is there a warm ocean beneath the icy crust and exactly how thick is that crust? A sounding radar must determine either the presence or absence of a subsurface ocean via a search for an ice-water interface, ice internal structure and possible surface topography variations.

Table 1 summarises the observational requirements for terrestrial, Martian and Europan ice-sounders. These requirements are not exhaustive or fully consolidated at this stage, and remain the subjects of further debate among the science communities.

Table 1 Summary of observational requirements for terrestrial, Martian and Europan ice-sounders

Parameter	Antarctica and Greenland	Mars	Europa
Surface elevation accuracy	≤ 1 m (from ICEsat and CryoSat)	≤ 20 m	≤ 20 m
Ice thickness	≥ 4800 m	≥ 4000 m	≥ 20 km
Vertical resolution	≤ 10 m	≤ 20 m	≤ 20 m
Basal condition (reflectivity resolution)	≤ 1 dB	≤ 1 dB	≤ 1 dB
Horizontal resolution	≤ Thickness/2	≤ 5 km	≤ 5 km

Discussion - SAR processing of BAS airborne data

Airborne radio echo sounding of the West Antarctic ice sheet in the region of Pine Island Glacier was performed in the austral summer of 2004/2005 under the National Science Foundation's West Antarctic Ice Sheet Initiative (AGASEA web-site). The British Antarctic Survey (BAS) flew its newly developed 150MHz ice-sounding radar over Pine Island Glacier and collected approximately 35,000km of sounding data. Extended off-nadir echoes from the rough air-ice interface adversely affect such an airborne ice-sounding radar system. The surface clutter obscures echoes from internal reflecting layers, whilst the diffraction hyperbolae from the rough bedrock limit the along-track resolution. In the area of Pine Island Glacier, the bedrock is particularly deep (more than 2km), and in some areas has never been detected. Enhancement of the sounding capability in those difficult areas through adequate data processing was of crucial importance to the scientific community.

A collaborative effort between BAS and the European Space Agency (ESA) was undertaken for developing synthetic aperture radar (SAR) processing algorithms and applying them to the Pine Island radio echo data (Hélière, 2007). Such techniques are able to attenuate surface clutter in the flight direction using Doppler information in the echo signal, hence enhancing the detection of sub-surface signals. Fig. 1 shows a comparison of a 20km long echo profile along a sub-glacial valley both before (a) and after SAR processing (b). Improvements are most obvious at the beginning of the flight-path where the sub-glacial valley is very deep – corresponding to an ice thickness of nearly 3000m. Focused SAR processing is able to attenuate surface clutter returns that mask low level echoes, hence extending the bedrock detection threshold from a depth of 2000 to 3000m. The complete set of sounding data from the Pine Island Glacier campaign is now being processed at BAS using the developed SAR algorithm for further improving the existing sub-glacial topography map (Vaughan et al., 2006). Here, the main interest is to fill the gaps in the areas where the bedrock was not previously detectable (areas of deep sub-glacial valleys).

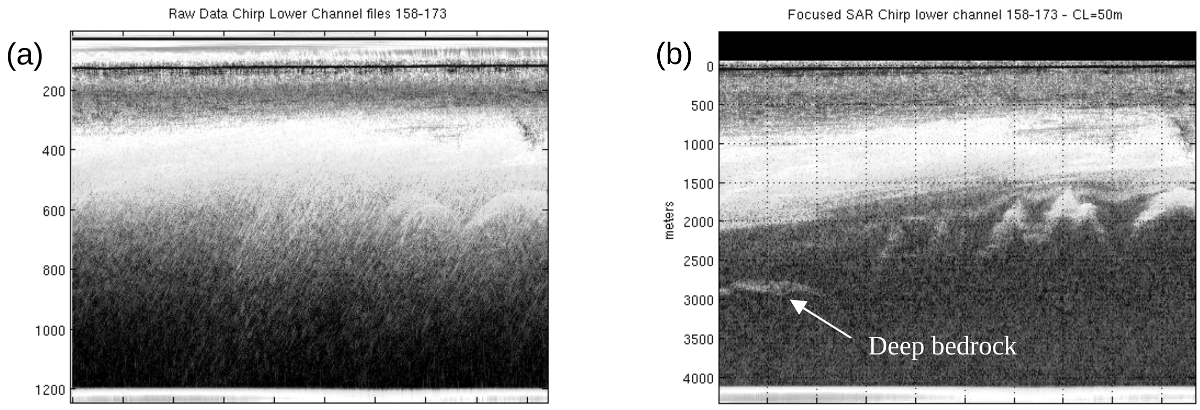

Figure 1. Echo profile along a sub-glacial valley: (a) Raw data with a combination of coherent and incoherent summation of complex data; (b) Focused SAR processing with 50m synthetic aperture length, followed by incoherent summation.

Discussion - IceSAR 2007 campaign and P-band ice-sounding demonstrator / IPY 2007-2008

The above-described result demonstrated the feasibility of sounding ice sheets down to a depth of 3000m at 150MHz (VHF) over West Antarctica. Unfortunately, no equivalent experience exists from any sounding campaign at P-band, and it is essential to understand the wave scattering/refraction at the air-ice interface and propagation within the ice sheet at this frequency region. As a first step towards answering these questions, the IceSAR campaign was organised by ESA from mid March to mid April 2007 in collaboration with the German Aerospace Centre (DLR), Alfred Wegner Institute, Norwegian Polar Institute, University of Oslo and Scot Polar Institute. Such collaboration was made possible under the context of the International Polar Year 2007-2008. DLR's airborne E-SAR system including P-band (350MHz) radar in both side-looking SAR and nadir configuration was deployed over the Austfonna Ice Cap. In addition to the E-SAR system, 'snowmobile-pulled' Ground Penetrating Radar (GPR) measurements operating at 800MHz were carried out by the Norwegian Polar Institute along one of the flight-paths. Multiple, parallel flight-path acquisitions in nadir-pointing mode were performed for attempting tomographic data processing techniques, as well as acquisitions made using side-looking geometry for interferometric SAR processing. At the time of writing, the first half of the campaign had been completed.

The lack of an adequate airborne radar system operating at 435MHz for acquiring representative sounding data led ESA to fund the development of a demonstrator capable of being operated in Antarctica. The development contract was awarded to the Technical University of Denmark, the Institute of Electromagnetic Systems (Dall, 2006). Table 2 summarises the high-level instrument specification. The system bandwidth will be selectable from 6MHz (ITU allocation for space-based observations) to a maximum of 85MHz for high resolution sounding. The carrier aircraft was selected to be a De Havilland DHC-6 Twin Otter, the type already deployed by BAS for Antarctic campaigns. For minimising surface clutter from the off-nadir across-flight direction, a planar antenna of 1800mm × 480mm aperture will be mounted below the fuselage with its long dimension in the across-flight direction (for providing a narrow antenna beam in the across-flight direction). A 4-phase-centre antenna concept has been adopted which will enable the synthesis of a nadir sounding beam as well as off-nadir beams with a null at nadir as depicted in Fig. 2 (in red and blue, respectively). Post processing of data from the two channels shall enable coherent subtraction of the clutter signal from that of the nadir sounding beam, consequently reducing the off-nadir clutter which masks the deep echoes. The limitation of the two-channel system is its inability to cope with asymmetrical surface topography with respect to the flight-path. For enabling surface clutter reduction under more general ice topography, a further extension of the system to 4 channels and a larger antenna (in across-flight) is planned, enabling the technique to be tested from a higher flight altitude. The first test-flight of the demonstrator over Greenland is planned to be held towards the end of 2007. Further campaigns are being considered in the context of IPY 2007-2008.

Table 2 P-band ice-sounding demonstrator specification

Centre frequency	435 MHz
Bandwidth	6 - 30 MHz (85 MHz goal)
Polarization	Quad
Pulse length	33 ns - 50 μs
Peak power	100 - 300 W
Maximum PRF	20 kHz
Range sidelobe	≤ -60 dB
Across-track clutter suppression	Multiple phase-centre antenna
Operating altitude	150 - 3500 m
Operating environment	Antarctica

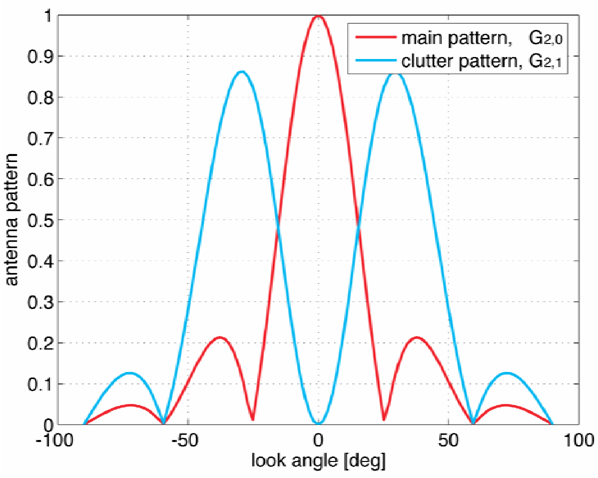

Figure 2. Nadir sounding beam (red) and off-nadir beams (blue) of the P-band demonstrator antenna.

Discussion - Advanced Concept for RAdar Sounder (ACRAS)

A study was initiated by ESA for exploring advanced radar techniques for ice sounding over Earth, Mars and Europa (ACRAS web-site). The objective of the study is to assess the feasibility of new measurement concepts for sub-surface sounding using along and across-track processing and techniques in order to decrease the impact of clutter and enhance the resolution and contrast. Furthermore, the ionospheric fluctuations over Earth and other planets such as Mars introduce phase variability of the radar signal, limiting the utility of such new concepts that make use of synthetic aperture processing. Better modelling of the ionosphere, adding real-time corrections using dual-frequency techniques like GPS/Galileo, or auto-focusing techniques to overcome small-scale variations need to be developed in order to mitigate such disturbing effects. The study is led by Vexcel together with BAS and DLR as experts in terrestrial applications, and Max Planck Institute in Lindau and Laboratory of Planetology in Grenoble for planetary applications, complemented by EADS Astrium Ltd. for the space system aspects. The observational requirements as listed in Table 1 form the initial basis for this investigation. Various clutter suppression techniques are analysed, such as a multi-phase-centre antenna approach and a multi-pass tomographic processing technique. In addition to new sounding concepts, advanced processing algorithms will be developed which will be applied to airborne radio echo sounding (e.g. from the IceSAR campaign and P-band ice-sounding demonstrator) and MARSIS data for validation.

Discussion - BIOMASS P-band SAR Earth Explorer Core mission candidate

The Second Call for Earth Explorer Core Mission Ideas was released by ESA on March 15, 2005. Twenty-four proposals from the Earth science community were received and subsequently subjected to detailed scientific and technical assessment. Among the six mission ideas selected, BIOMASS is envisaged to carry a P-band SAR for global observation of above-ground biomass and other geophysical parameters associated with forests. Its overall objective is to reduce uncertainty in the worldwide spatial distribution and dynamics of forests leading to improved present assessments and future projections of the carbon cycle. This overall objective is addressed through the exploitation of a P-Band SAR mission to provide the following key information products at global scale: (1) gridded estimates of above ground forest biomass; (2) estimates of areas of disturbance and monitoring of forest recovery over time; (3) estimates of areas of wetland inundation.

Secondary mission objectives of BIOMASS arise from the opportunity of exploring the Earth's surface for the first time with a long-wavelength SAR system. New information is expected in the following areas:

- Polar ice sheets including the structure of the sub-surface layers and ice thickness above the bedrock;
- Sub-surface imaging in arid areas.

The preliminary P-band SAR system/observational requirements are summarised in Table 1. Two distinct observation configurations are ideally necessary in order to cover the primary and secondary mission objectives. Forest observations and other imaging applications will require the conventional side-looking configuration, whereas deep sounding of the Antarctic ice sheet would require nadir viewing configuration, which feasibility will be assessed after the optimisation of the system in side-looking configuration. Also for the latter objective, the choice of a sun-synchronous orbit would inevitably leave an important observation gap around the South Pole, i.e. over the central part of Antarctica. The six candidate missions are in phase 0 (pre-feasibility study) and current planning anticipates the launch of the selected Earth Explorer mission in the 2014/2015 timeframe.

Table 3 Preliminary BIOMASS system/observational requirements

Parameter	**Side-looking mode** (baseline for forest biomass and subsurface imaging)	**Ice-sounding mode** (subject to system capability accommodation)
Centre frequency	435 MHz (P-band)	
Bandwidth	≤ 6 MHz (ITU allocation)	
Polarisation	Full polarimetry and/or circular Tx and dual Rx and/or dual-polarisation	
Incidence angle	≥ 25°	0°
Orbit	Sun-synchronous 5-6 AM/5-6 PM	
Coverage	Global every ≤ 25 days	Complete one-time coverage of Antarctica and Greenland
Spatial resolution	≤ 50 m × 50 m (4 looks)	≤ TBD
Swath width	≥ 110 km	No swath in vertical sounding mode
Noise equivalent σ^0	≤ -30 dB	≤ TBD
Absolute calibration	≤ 1 dB	

Summary - Future perspectives

ESA's BIOMASS Earth Explorer candidate mission represents a realistic opportunity to operate high sensitivity P-band radar aboard an Earth-orbiting satellite by the 2014/2015 timeframe. Although the mission is intended primarily for the forest-biomass observation in a conventional side-looking SAR configuration, there are strong interests among the ice sheet community for imaging the subsurface over Antarctica and Greenland, and possibly experimenting sounding in nadir configuration (if the system design permits satellite re-pointing). The above-described efforts are all intended for assessing the feasibility and for predicting the performance of satellite-based sounding missions, with a particular emphasis on further consolidating the ice sheet observation requirements.

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